ROLLOVER CRASHES – REAL WORLD STUDIES, TESTS AND SAFETY SYSTEMS

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ABSTRACT

The improvements of car safety have focussed from frontal to side protection during the 90ies. Currently rollover protection is one of the ongoing next steps. Existing and modified hardware like seat belts with pretensioners and side airbags are able to protect car occupants in rollover crashes well. Enhanced safety hardware products and strategies are in production and under further development.

To integrate rollover protection into a car safety system the trigger philosophy is one of the key points. Full-scale rollover crash tests provide basic information about the function of sensors and algorithms to trigger the relevant protection devices. After optimising these devices full-scale tests show the behaviour and possibilities to tune the protection performance parallel and in addition to numerical simulations. Several rollover test procedures are established and in use. The official FMVSS-208 rollover is supplemented by some other rollover tests like cork screw, embankment, curb trip and sandpit rollover. The aim is to test the behaviour of the protection system and its components in critical roll and no-roll situations – from some technical points of view and in correlation to relevant real world accident scenarios.

This article gives an overview of real world accident scenarios and shows statistics based on literature reviews, federal statistics and DEKRA´s accident research. Rollover tests conducted by DEKRA and other test facilities by order of OEM's and suppliers are shown. Purposes, advantages and disadvantages of the tests are discussed.

Additional information from AUTOLIV about rollover protection hardware and trigger strategies complete this discourse.

INTRODUCTION

The safety of cars has been improved with the focus on frontal impacts first. During the 90ies, side protection became more important. Ongoing next steps to improve vehicle safety will lead to an enhanced overall safety to protect occupants and other road users as good as possible in several types of all relevant real world accident scenarios. The ultimate goal is given by "vision zero" [1]. Among the next steps, which are not only a vision but already reality, is rollover protection. Existing and especially tuned safety features like seat belts with pretensioners and side airbags are able to protect occupants in rollover crashes well. With ongoing first steps it is possible to use this hardware for extra benefit. For this, it is necessary to activate these protection systems right in time also in rollover crashes. For further improvement of rollover protection, some hardware modifications or supplementary developments could be helpful.

To integrate rollover protection into a vehicle safety system, one key point is the trigger philosophy. Some theoretical models to find and describe trigger algorithms exist. Full-scale rollover tests and accident simulations are necessary in parallel to numerical simulations to validate the basic theoretical models and their application to a particular vehicle. Full-scale tests can also complement existing virtual rollover test scenarios (Airbag 2002, Krabbel, G). This field of research and development is relatively new. To cover the relevant scenarios that have been defined so far, several test procedures are established and in use. The official FMVSS-208 rollover has been supplemented by some other tests with different kinematics and trigger circumstances. As shown in this article, so called corkscrew, embankment, curb trip and sandpit rollover are in use. These samples of different tests provide basic information about how sensors and algorithms can trigger the relevant protection devices in principal and how robust the trigger can be generated. It is also tested whether the protection hardware works as designed and if there are any possibilities of enhanced tuning.

As in real-world rollover crashes, the test scenarios show a large variety of the kinematics before and after rollover. Usually there is a tripping phase before, an airborne phase during and a ground impact after the rollover. This can be repeated some times. The triggering criteria, car damages and occupant injuries (or dummy loads) are often different in similar scenarios. Real-world accident studies for Europe show the majority of car occupants after a rollover slightly or even uninjured. US studies contrarily show a higher rate of severely injured or killed car occupants after rollover. This can be explained by different types of vehicles and belt use rates. Ejected occupants have the highest risk of being severely injured or killed in a rollover crash.

REAL-LIFE CRASH INVESTIGATIONS

A literature review showed, that rollovers did always occur and became object for accident research. Huleke et al. (1973) and Hight et al. (1972) studied rollover crashes on US roads in the early 70ies. Some fundamental knowledge was found at that time. For example, the investigations showed, that only 2 % of non-ejected occupants were critically injured or killed (AIS 5+). Contrary to the 47 % of critically injured or killed occupants which have been ejected.

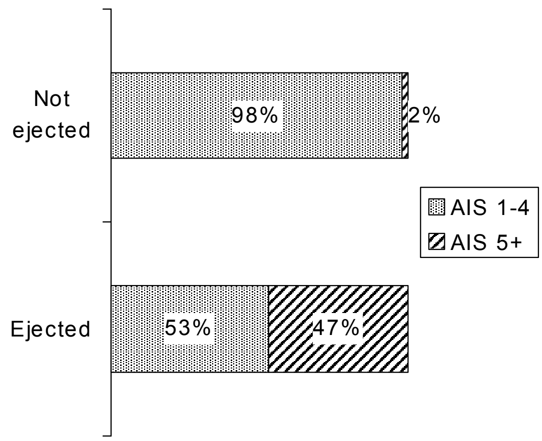

Figure 1. Shares of critically injured or killed (AIS 5+) vehicle occupants in rollover crashes separated into ejected and non-ejected occupants (Huelke et al. 1973, Hight et al, 1972)

The situation on German roads has been analysed by Otte (1989). He discovered, that in 202 rollover crashes with 35 % of the occupants belted, only 4 % were critically injured or killed. This is similar to the outcomes for a group of 5,149 non-rollover accidents with 40 % of the occupants belted and only 4 % of them critically injured or killed, Figure 2. 21 % of the occupants involved in rollover crashes were uninjured (AIS = 0). The share of uninjured occupants in the non-rollover group is more than doubled with 56 %.

Another 30 German rollover crashes were analysed by Miltner and Wiedmann (1997). These crashes occurred at speeds between 55 and 180 kph involving 79 passengers. 41 (52 %) of them were belted and 38 (48 %) were not. 10 (24 %) of the belted and 22 (58 %) of the unbelted occupants suffered fatal injuries, Figure 3. Amongst the belted occupants 2 (5 %) were ejected. Contrary to this, the share of ejected occupants was 26 (68 %) for the unbelted occupants.

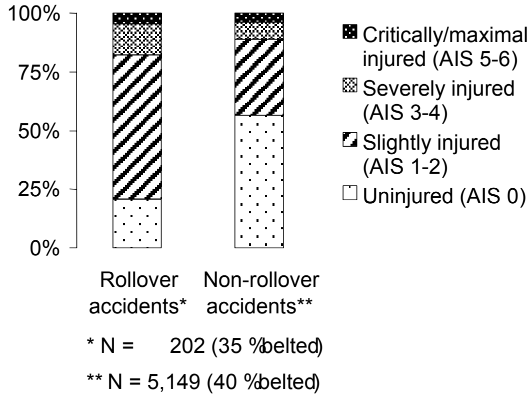

Figure 2. Shares of uninjured and AIS-classified injured occupants in rollover crashes and non-rollover crashes in Germany (Source: OTTE, 1989)

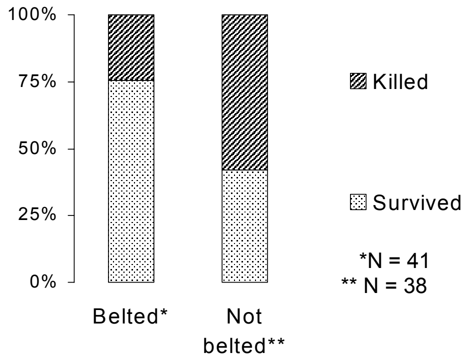

Figure 3. Shares of killed and survived car occupants in 30 German rollover crashes with 79 occupants involved (Miltner and Wiedmann, 1997)

New results regarding rollover crashes in the USA are provided via internet by the NHTSA (see Figure 3). The National Automotive Sampling System (NASS) reported, that there were 3.4 million light vehicle tow-away crashes per year from 1995 to 1999. The share of rollovers is 7 % among these accidents. The Fatality Analysis Reporting System (FARS) indicates 31,921 vehicle occupants killed in total in 1999, 31 % of them in rollover crashes. This confirms the higher relevance of rollover amongst the severe crashes.

The share of rollovers did not only depend on the severity of the crash. The type of vehicle is also a determining issue. FARS reported for the year 1999, that 22 % of the car occupant fatalities occurred in rollovers. With 47 % this share is significantly higher for occupants of LTVs (pick ups, sport utility vehicles and vans), Figure 5.

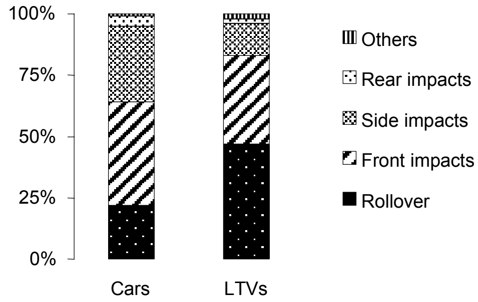

Figure 4. Shares of crash types for light vehicle crashes from US National Automotive Sampling System (NASS) and from US Fatality Analyses Reporting System (FARS)

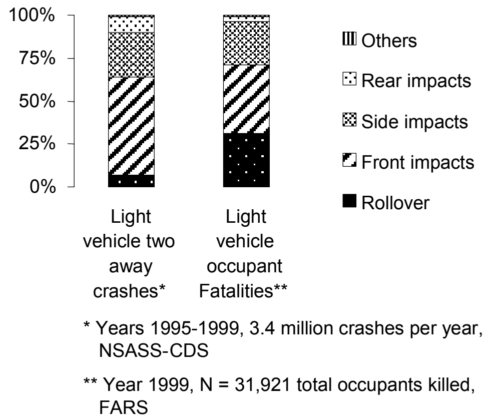

Figure 5. Shares of occupant fatalities for different crash types separated for cars and LTVs (pickups, sport utility vehicles and vans) reported from US Fatality Analyses Reporting System (FARS 1999)

It was detected, that the share of rollover fatal crashes among the LTVs is the highest for SUVs (63 %) followed by pickups (43 %) and vans (41 %). Figure 6 gives an illustration of this, compared with the share of 22 % fatal rollover crashes for cars.

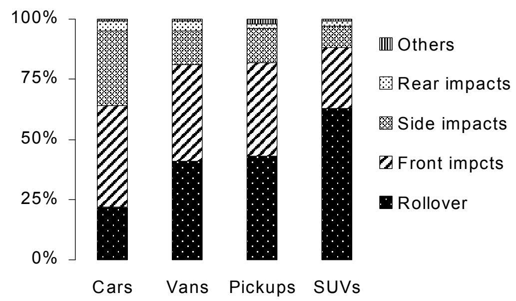

Figure 6. Shares of occupant fatalities for different crash types separated into cars, vans, pickups and SUVs from US Fatality Analysis Reporting System (FARS, 1999)

Some information about the situation in Australia is reported by Rechnitzer and Lane. 19 % of the fatal crashes on Australian roads (paved and unpaved) involve a rollover. Rollovers are mainly single-vehicle accidents in Australia. They occur predominantly on rural roads at high speed and at night.

ROLLOVER CRASH CHARACTERISTICS

Rollover crashes are complex events. They are influenced by the road and vehicle characteristics as well as by the interaction of the driver and the environmental factors. It is an actual task of the real world accident research to describe rollover crashes with the relevant characteristics and items. Because rollover is a world-wide subject, the used systematic to investigate rollovers needs to be harmonised world-wide, too. The following description shows a few insights into one example of a case collection that is currently build up at the DEKRA Accident research.

The crash occurred on a German Autobahn. A car collided with another car. The speed was reconstructed in the range of 120 to 140 kph. After the initial collision the car skidded and got off the road. After 50 m the car collided with the embankment and hit a noise-protection wall. After this second impact the car skidded back on the road and reached its final position after approx. 90 m (see figure 7).

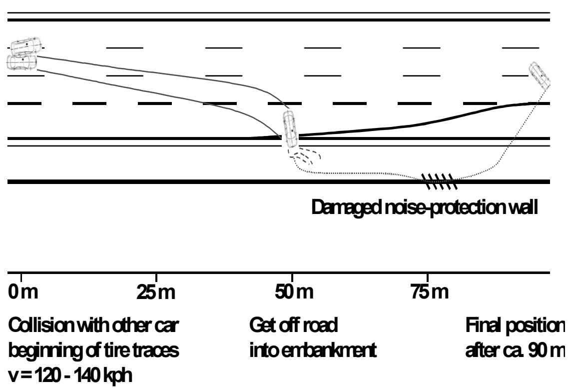

Figure 7. Course of a rollover with a car colliding with another car and then with a noise protection wall on a German Autobahn (DEKRA database)

The rollover was caused by the impact on the noise-protection wall. In its final position, the car lay on its roof and burned out (see Figure 8). All 3 car occupants were killed.

Figure 8. Additional illustration of the rollover crash shown in figure 7 with tire marks in direction to the noise-protection wall and the burned-out vehicle (DEKRA database)

Otte (1989) found out, that 50 % of the rollover crashes examined by his team occurred on straight roads and 33 % in a curve, Figure 9.

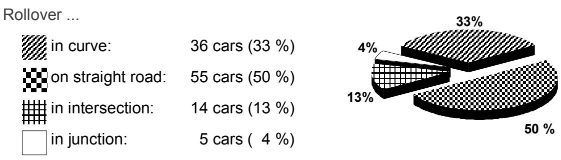

Figure 9. Road characteristics for rollover crashes (Otte, 1989)

To describe and study the kinematics of rollover crashes, several points must be considered. A simplified view of the relevant motion sequences for a rollover is given in Figure 10.

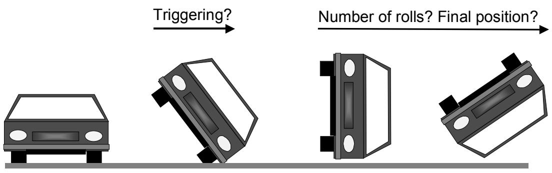

Figure 10. Some points of interest to describe rollover kinematics

One important question deals with the cause of a rollover. Here the crucial event is the trigger. First analyses from DEKRA´s rollover-crash database show, that from a total of 58 vehicles involved in a rollover crash 18 (31 %) of them had no impact before the first rollover. 35 (60 %) of the vehicles had one impact and 5 (9 %) had two impacts before the first rollover (Preßler, 2002). 22 (55 %) of the 40 pre-rollover impacts occurred with another vehicle, 17 (43 %) with a fixed obstacle and 1 (3 %) with other objects (see Figure 11. Preßler, 2002).

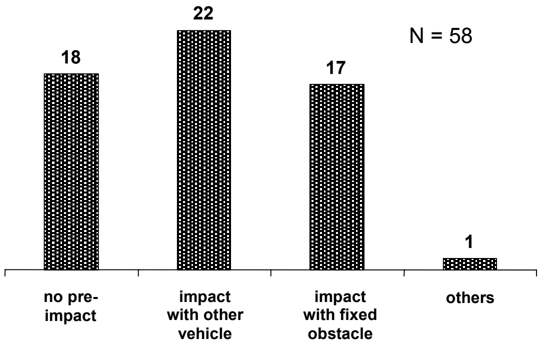

Figure 11. Absolute frequencies of pre impacts of vehicles before rollover (Preßler, 2002)

For the rollover crashes examined by Otte (1989) it was found, that 65 (58 %) were caused by skidding only, 36 (32 %) resulted from a collision with another car, 2 (2 %) from a collision with an object and 9 (8 %) of the cases the cause for the rollover was braking or others influences, Figure 12.

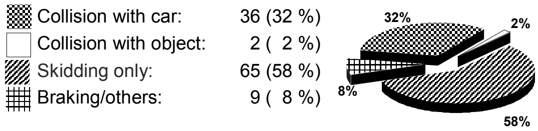

Figure 12. Causes of rollovers (Otte, 1989)

Under given circumstances the occurrence of a rollover depends also on various roadside conditions. Figure 13 gives a schematic overview.

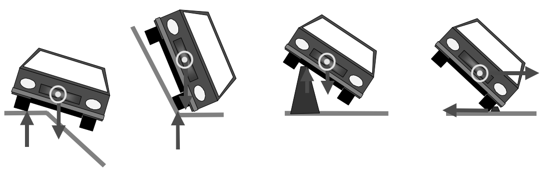

Figure 13. Schema of roadside conditions that influence the triggering of a rollover

Dynamic conditions depending on forces, momenta and speeds are at least crucial factors for the triggering of a rollover, figure 14. These parameters also influence the kinematics after the initiation of a rollover.

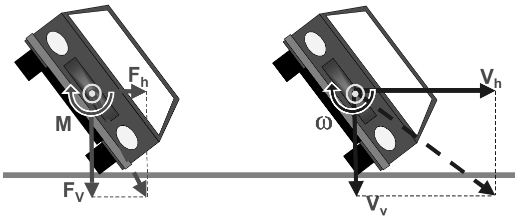

Figure 14. Dynamic parameters to describe conditions at triggering

When a trigger is given and the rollover occurs, the car can only tilt to the side or run into one or more rolls. The final position could be on the wheels, on the right-hand or left-hand side or on the roof. This may influence the damage of the car and the rescuing of the occupants after the accident.

First analyses of DEKRA´s rollover-crash accident database show the final position of most vehicles either laying on the roof or standing on its wheels, Figure 15 (Preßler, 2002). The reconstruction of the number of rolls is very difficult and remains often unclear especially for multiple rolls.

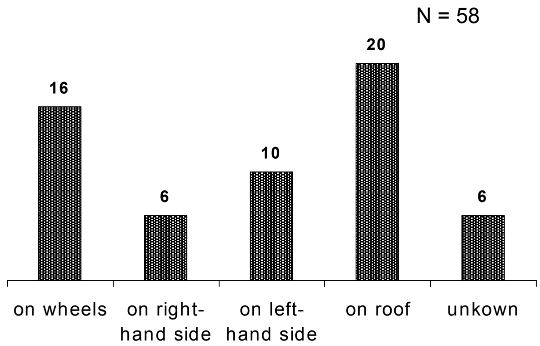

Figure 15. Absolute frequency of the orientation of the vehicle in final position after rollover crashes (Preßler, 2002)

In addition to the kinematics and with regard to the occupant protection, it is interesting to know how the car is damaged and how the occupants move, receive impacts and suffer injuries during the rollover. For example Miltner and Wiedmann (1997) reported, that ejected occupants mainly suffered injuries at their body and spine. Occupants which remained in the car suffered injuries mainly at their head and extremities, Figure 16.

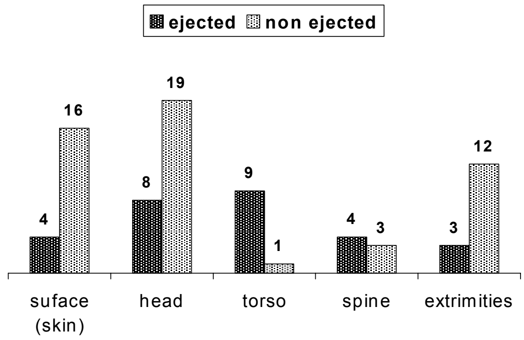

Figure 16. Most severe injured body regions of car occupants after rollover crashes separated into ejected and non-ejected (Miltner and Wiedmann, 1997)

ROLLOVER CRASH TESTS

Berg et al. (1992), described hardware rollover crash tests which were conducted in the 80ies in particular to reconstruct accidents. At the present time some more relevant variations of real-world rollovers have to be constituted for the development of occupant protection. The following gives an overview of some of the tests that have been carried out by DEKRA by order of OEMs and suppliers since the last few years.

Embankment tests (see Figure 17) deliver basic information. Acceleration and roll-rate signals are superposed by vibrations and noise, very similar to real-world off-road scenarios. The robustness of the algorithms of the triggering devices can be analysed. Such tests are run with realistic behaviour of car and occupants under given off-road circumstances. The vehicle is leaving the road into the embankment under different slope angles with or without steering. The reproducibility of such tests is low, because the roll triggering depends on the car's own behaviour, the ditch configuration and the approach angle.

Figure 17. Embankment rollover test

A special ramp is necessary to run the so-called **corkscrew rollover**, (see Figure 18). Such a test is useful for scenarios with slow roll motion around the longitudinal axis of the car. This test helps to develop the triggering algorithms for belt pretensioners and head protection systems in slow-roll events similar to high-speed real-world rollovers on rural motorways. The results of the test depend on the corkscrew ramp which has to be defined properly.

Figure 18. Corkscrew rollover test

Also close to real-world scenarios is a **curb-trip rollover** after pre-sliding of the car (see Figure 19). Such a test is useful for sensor and algorithm development for medium roll conditions. The sideways movement of the occupant's head and torso during the car sliding before the wheel impact on the curb is of interest for the development of head protection systems and belt pretensioners. The reproducibility of such tests is low and depends on both, the kinematics and the car's own behaviour (e.g. stability of the wheels and axles)

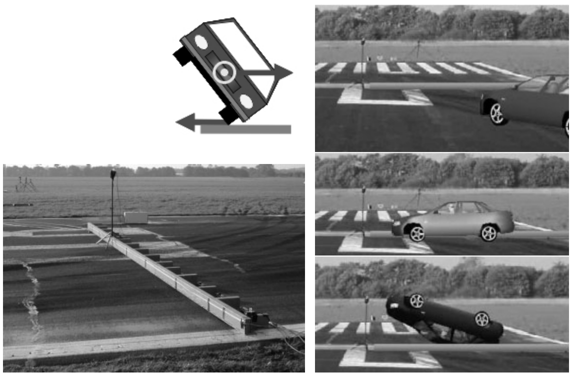

Figure 19. Curb-trip rollover test

To date, the only rollover test procedure for cars embodied in law so far is the so-called **"FMVSS-208 rollover"** (see Figure 20). To run this test, a sled is used. The car on it is inclined under 23°. The test velocity is 49 kph. This test is useful for sensor and algorithm development under high roll conditions around the longitudinal axis of the car without velocity component in longitudinal direction. The number of rolls can vary from 1 up to 3 or more under the same conditions.

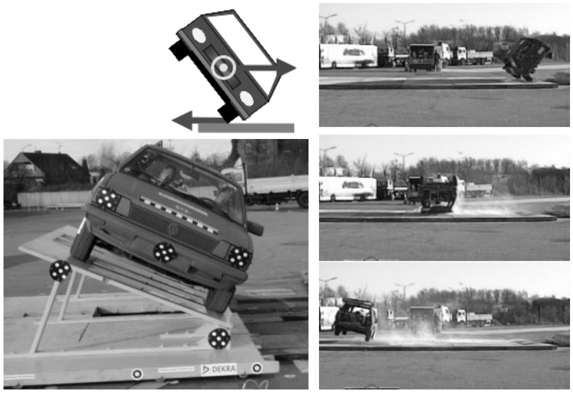

Figure 20. FMVSS-208 Rollover

A **sandpit rollover** has also a lateral movement only. The car stands on a sled and slides sideways into a sandpit (see Figure 21). This test is useful for sensor and algorithm development for low-roll conditions and helpful to develop triggering algorithms for head protection systems and belt pretensioners. The roll conditions depend on the car velocity and the consistency of the sand in the embankment.

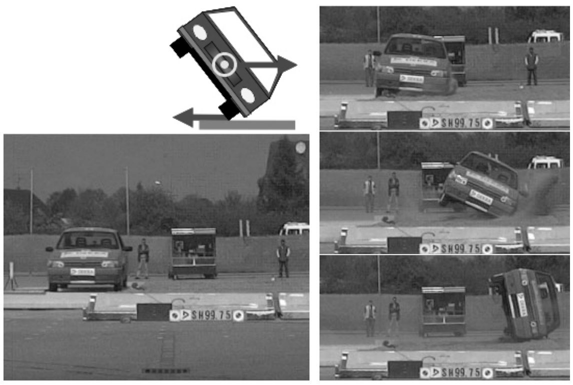

Figure 21. Sandpit rollover

Hardware rollover test results are not only useful for the development and validation of triggering algorithms. The conversion of kinetic energy during the roll (provoked by friction between the sandpit and the vehicle) into deformation energy results in multiple structure damages. These damages can be studied, as described in principle by Friedewald (1994). The schema is shown in Figure 22. Only a small amount of kinetic energy is converted into deformation energy in contrast to frontal or side impact crashes.

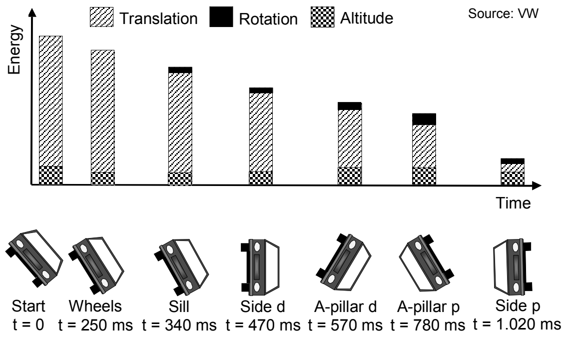

Figure 22. Schema to describe absorption of energy during rollover (Friedewald, 1994)

The car is mainly damaged in the roof area during the rollover. Friedewald (1994) proposed a roof deformation type classification as shown in Figure 23. For example, there can be longitudinal folds in the roof, collapsed pillar(s) or a totally crushed down roof. Not all of these deformation types lead to a significant reduction of the life-saving internal space. Not only the ground impact phases during rollover, but also the car body structure influences the pattern of roof deformation. Friedman and Nash (2001) reported that some weak, antiquated roof designs contribute to severe head and neck injuries.

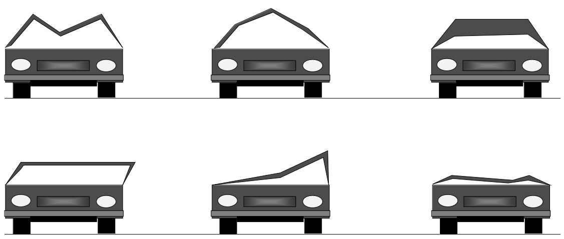

Figure 23. Schema to describe roof deformation pattern as proposed by Friedewald (1994)

Experiences with the roof-deformation schema proposed by Friedewald and the use of DEKRA´s rollover database have led to a modification. The separation of the roof into the front and the rear area was considered to be useful (Preßler, 2002). Results are shown in Figure 24. Often there was no roof deformation. Deformations of type 3 and 5 were the most frequent ones among the front deformations and the types 3, 4 and 5 were found as the most frequent ones among the rear area deformations.

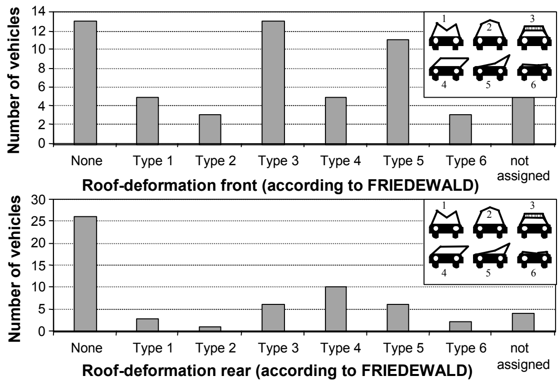

Figure 24. Modified roof area deformation separated into front and rear (Preßler, 2002)

Mostly Hybrid-III-dummies are in use to represent the occupants at rollover tests. This dummy type has been developed for frontal impacts and its biofidelity is not satisfying for lateral loads. But partial ejection (for example arms passing through open side window) can be observed by using this dummy that is equipped with upper extremities. Some tests are run with side impact dummies (which are not equipped with arms) to study lateral loads to head and neck.

NUMERICAL ROLLOVER SIMULATION AS PREPARATION FOR REAL CRASH TESTS

As a service provider for the automotive industry, the DEKRA crash test centre performs the described crash test configurations including the embankment rollover, curb-trip rollover, "FMVSS 208 rollover" rollover into sandpit and the so-called cork-screw rollover. The vehicles are mostly irreversible damaged during the described tests. That's why the virtual simulation in the forefront of real crash tests gains more and more importance. One important aspect to implement the simulation procedures is to find out the border between the roll and no-roll event with a less number of real world tests. The second important reason for simulation is to reduce the number of the used test vehicles.

The hardware tests play a significant role for the automobile manufacturers regarding the stability of the passenger cab. However, the border between the roll and no-roll event is very important for the OEM to determinate the algorithms for the protection devices. Regarding these arguments, the software PC-Crash is a sufficient instrument to simulate these rollover crash tests. A sample of valid basic numerical simulation models has been developed by DEKRA for each of the described rollover crash tests (Hey, 2003). Figure 25 shows an example.

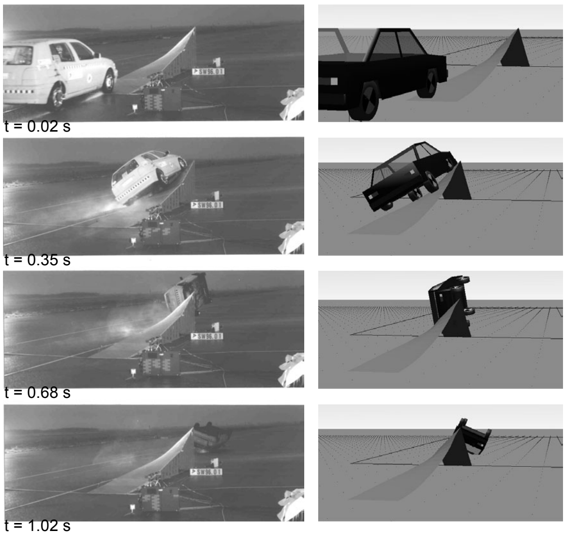

Figure 25. Comparison of a real world rollover crash test with a PC-Crash-simulation (Hey, 2003)

PC-Crash comes with a large vehicle database including basic parameters of a large variety of existing vehicles. The further properties of the real world rollover crash tests like the sandpit or the so-called cork-screw-ramp are not part of the program PC-Crash. These parts have to be generated additionally (Hey, 2003). Figure 26 shows the different final test positions after the sandpit simulation with modifications to the test velocity.

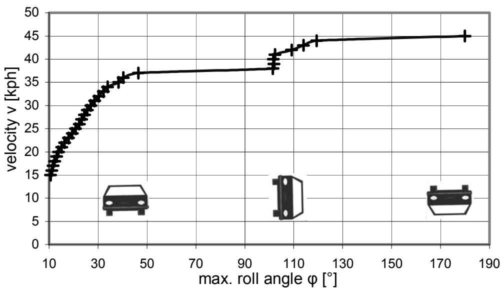

Figure 26. Influence of the velocity to the maximum roll angle φ at a simulated sandpit rollover

Up to a velocity of approximately 36 kph there is a no-roll event, in the range of approximately 37 kph to 44 kph the vehicle reaches a 90-degree end-position and beyond approximately 45 kph the vehicle reaches its final position laying on the roof.

After the numerical simulation the program can generate different diagrams, e.g. a path-time diagram or a speed-time diagram. Figure 27 shows the roll rate during the simulation.

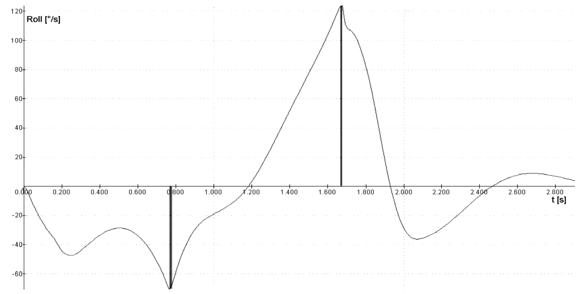

Figure 27. Diagram of the roll rate at a virtual simulated sandpit rollover

The diagram from a real world rollover crash (figure 28) shows the same characteristic as the one from the numerical simulation. Therefore the simulation with PC-Crash is an adequate instrument to predict the behaviour of the vehicle in a real world crash test.

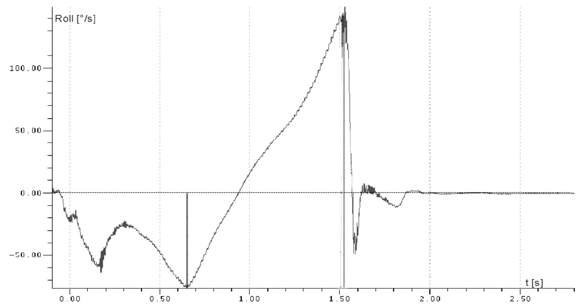

Figure 28. Diagram of the roll rate at a real world sandpit rollover crash test

Another important and interesting aspect is the possibility to generate a small movie from the simulation, figure 29. This feature enables inspect the motion sequence of the test in advance and gives the opportunity to get a rough impression of how the details of the rollover could look like.

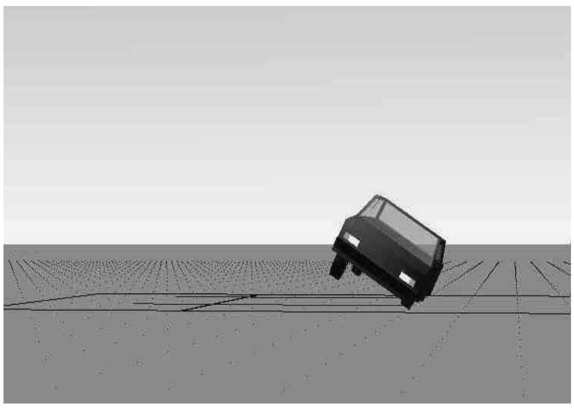

Figure 29. Simulated motion sequence of a virtual sandpit rollover crash test

PROTECTION OF OCCUPANTS

An effective rollover occupant protection system is based on minimisation of compartment, intrusion that could occur at several impacts of the car on the ground. Within the compartment the occupants have to be retained in their seats. Impacts, especially of the head with corresponding loads of the neck have to be cushioned and (partial or full) ejection has to be prevented. In this context the seatbelt plays a significant role. Supplementary devices such as pretensioners, load limiters and energy absorbers can improve the basic protection. In the future a high-integrated rollover occupant safety system may include inflatable head restraints and side window curtains, seatbelt pretensioners, seatbelt super-pretensioners, seatbelt retractor locks, active roll bar, pop up headrest or enhanced support structure for convertibles, rollover prevention techniques and serial data communication for post collision controls (Gopal et al., 2001). To activate reversible or irreversible protection systems, integrated algorithms have to interpret different signals from several sensors.

Figure 30 gives an impression of an existing Total Safety System. Today, conventional restraint systems like seat belts, front and side airbags (see Figure 31) combined with advanced systems are able to give the occupants “all around” safety in rollover crashes, too. For the right choice of the elements of such a protection system, it is necessary to know what happens to the occupants during the relevant rollover scenarios.

Knowledge from real-life accidents, full-scale tests and numerical simulations have lead to the following requirements of a state-of-the-art rollover protection system: Occupant protection is necessary up to 10 seconds after the rollover starts. Later on, if rescue of the occupants is necessary, it should not be hindered by components of the protection system. Ejection and leaning out of occupants and their extremities have to be avoided. Interaction between the occupants could also be an important issue.

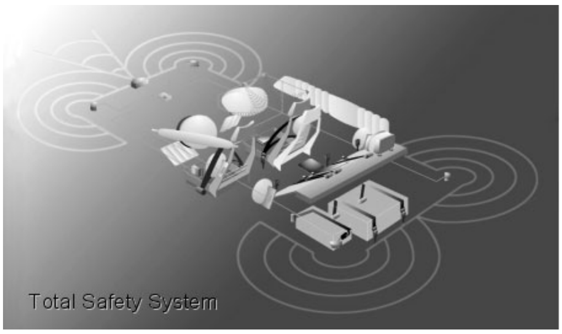

Figure 30. Total Safety System

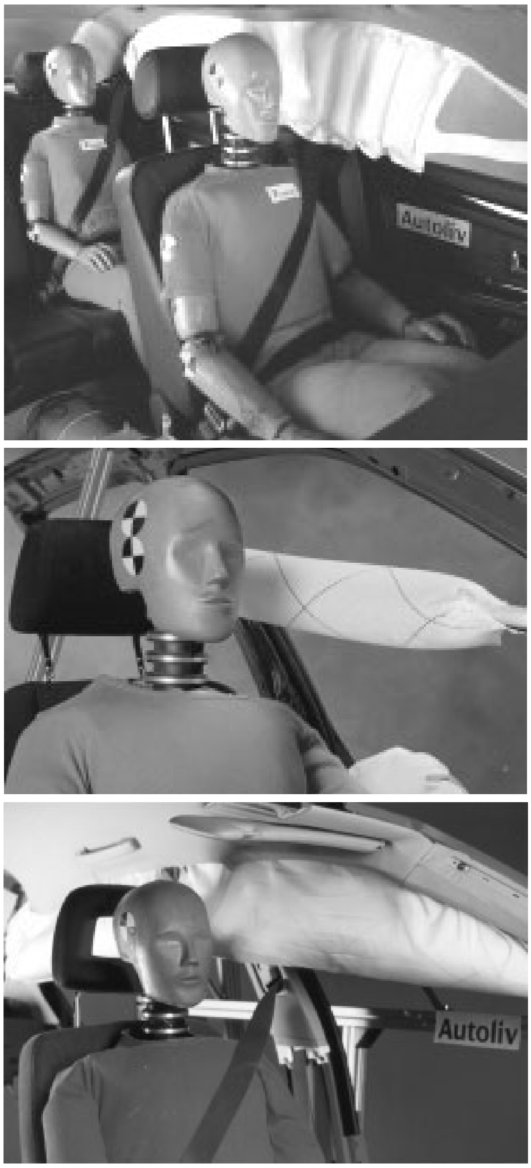

Figure 31 Different side airbags provide protection during rollover

This leads to a strategy of vehicle occupant protection with chosen system elements:

- Occupants must be fixed in the seats
- Possible loads to head and neck have to be reduced
- Preservation of distance between interior and occupants is necessary
- Interaction between occupants with corresponding injury risk has to be limited
- Possible intrusions into the compartment especially by the roof have to be prevented

The occupant protection system must be activated immediately after the beginning of inclination in order to guarantee its live-saving effect during the rollover. An algorithm only using the vehicle’s inclination angle or angular rate will not fulfil all requirements.

The AUTOLIV algorithm gains the decisive milliseconds by taking account of the speed of the vehicle. Another input of the algorithm is the rotation rate around the longitudinal axis and the lateral and vertical acceleration. The AUTOLIV algorithm consists of two main functions: The rotational energy criterion (REC) and the initial kinetic energy criterion (IKEC), Figure 32.

The Rotational Energy Criterion (REC) recognizes primarily ditch and ramp-type rollover. It provides a threshold value for angular velocity at a given inclination of the vehicle. If the threshold is exceeded, a trigger signal is given.

The Initial Kinetic Energy Criterion (IKEC) recognizes primarily the soil and curb trip rollover types. It provides a threshold value for the angular velocity, depending on the vehicle speed. The higher the speed, the lower the threshold. A trigger signal is generated if the threshold is exceeded. Additional conditions, based on lateral acceleration, help to stabilise this criterion.

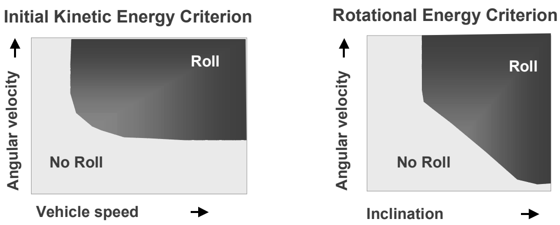

Figure 32. Schema for an advanced rollover trigger algorithm

CONCLUSION

After improving car safety in frontal, side and rear-end crashes, currently rollover crashes are on focus to give “overall protection” to the occupants. To protect vehicle occupants in rollover crashes, existing hardware like seat belts with pretensioners and side airbags are useful, too. Some enhanced protection equipment will supplement these “classic” protection systems in the future.

Rollover is on world-wide focus of accident research. The used systematic should be harmonised to reach more compatible results also for the relevant details. Looking to real-world rollover crashes a large variety of characteristics depending on vehicle behaviour and roadside conditions can be seen. Rollover crashes occur as single accidents at high speed on road or off road or after a collision with an opponent or obstacle even in low speed crashes. Unbelted occupants are most endangered to suffer severely or fatal injuries after ejection. But in some cases, belted and not or only partially ejected occupants suffer severe or fatal injuries during a rollover, too.

To develop and validate state-of-the-art protection systems several rollover full-scale test procedures are necessary and in use. Protection strategy and system components for occupant protection during a rollover have to prevent partial or total ejection and injury-critical loads especially to the head and neck of the belted occupants. It has to be tested weather the sensors and algorithms trigger the components of the rollover protection systems right in time. This depends on the roll conditions that could be fast or slow, with or without transversal movement, with tripping phases, airborne phases and ground impacts. The performance of the car body to ensure the survival space within the compartment is also amongst the points of interest. To minimise the number of conducted hardware tests and used test vehicles it is advantageous to accompany those tests with virtual pre-simulation.

Even in a rollover crash basic protection is given by a worn safety belt, which especially prevents ejection. Therefore belt wearing is absolutely necessary for vehicle occupants. This should be pointed out again. The actual enhanced supplementary rollover protection systems and those to come cannot work as effective as they are designed and developed for without the use of the safety belt.

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